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6. TITLE: "High-throughput planar glass coating using Laser Reactive Deposition (LRD)"
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High Throughput Planar Glass Coating using Laser Reactive Deposition (LRD™)

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ABSTRACT

Planar Lightwave Circuit (PLC) technology has been considered as a promising route to integrate a greater number of channels and more optical functionalities onto a small foot print, enabling smaller device sizes and lower costs of manufacturing by using existing semiconductor process technologies. Among several planar technology platforms, silica-on-silicon technology comprised of a silica higher index core and lower index clad has taken the lead in this direction. One of the major advantages of silica based PLC technology is its relative ease to couple to a single mode silica fiber because of a close match of the index and dimensions of the waveguide core of planar chip and fiber. In this structure, to completely confine and guide light signals, the silica layer stack, including lower clad, core and top clad can be as thick as 20 - 40 microns, in which the core layer thickness is around 6 – 8 micron. This has presented a major challenge to several major silica film deposition technologies including CVD, FHD, PVD, and Sol-Gel processes. In addition to basic requirements for optical quality of the glass film, low cost manufacture also demands a high deposition rate to reduce process costs in the fabrication of these planar chips. In this paper, we present a high throughput and planar glass coating technology to lay down doped and undoped glass films at a unprecedented rates. The technology is comprised of a laser reactive deposition (LRD™) process developed based on our nanoscale particle manufacture (NPM™) methods pioneered by NanoGram Corporation. We report results on planar glass films deposited using this technology and describe the concepts employed using this technology in manufacturing. Furthermore, we will compare it with various existing glass film deposition technologies.

Keywords: planar lightwave circuit, waveguide, CVD, FHD, LRD, glass, nano, particles, flame, silica, materials

INTRODUCTION

Recent explosion of internet data traffic and other high speed communication needs have motivated world wide efforts to develop fiber optical communication networks that continue to increase its bandwidth. As it is very expensive to lay down fibers into the ground, Dense Wavelength Division Multiplexing (DWDM) technology has been adopted to enable a dramatic transmission capacity increase over existing optical fiber networks. In this technology, light signals with multiple wavelengths are lunched and transmitted in a single mode optical fiber. Various equipment systems based on DWDM technology have been developed to send, route, amplify, receive and process these light signals. The system development has generated a strong demand on various component technologies such as lasers, amplifiers, detectors, modulators, attenuators, mux/dmux, filters, transivers and signal monitors[1]. At the moment, majority of these component devices have been produced using optical fibers and multi-layer dielectric thin film filters. In most cases, they are built into individual and discrete optical components to achieve the desired target use in a system. The cost of making these individual components is high due to extensively manual driven fabrication and packaging processes. With increasing demands for network capacity, further deployment of DWDM technology in long haul and upcoming metro markets, while keeping the costs down, will demand integrating more channels on smaller footprints. In addition, more functionality such as wavelength separation, amplification and signal filtering and monitoring are desired to further integrated device functionalities and increase reliability. These integration needs have posed a major challenge to current component device fabrication approach based on fibers and thin film filters.

Single mode fibers have been used to produce components such as splitters, couplers, Bragg gratings and amplifiers (e.g. EDFA). Fibers have several advantages. First of all, a single mode silica fiber has an extremely low propagation loss (0.5 db/km) as demonstrated in the success of long haul communications. It is produced by a fiber drawing process in which a glass preform is melted at high temperature (~ 1700 C) while fiber is being drawn from the melt. The high temperature drawing process is one of the key steps to produce glass fibers with a smooth interface between core and clad. The preform is made of a body of glass formed by reacting high purity reactant chemicals such as $SiCl_4$, also at a high temperature. $SiCl_4$ and several other Si-based precursor chemicals such as $SiHCl_3$ are high vapor pressure neat liquid chemicals. They can achieve exceptional purity by a repeated distilling. Therefore, high purity precursor chemicals, high temperature preform fabrication and high temperature fiber drawing are key factors contributing to the extremely low loss characteristics of single mode optical fibers. Secondly, fiber based devices can be coupled to communication fiber networks and other fiber based devices with mode matching properties that minimize the coupling-induced loss because of fiber-to-fiber arrangement. Coupling loss is one of the major loss factors in overall insertion loss specifications for fiber based devices. As many optical equipment systems require cascading component devices, propagation losses and coupling losses can add up when several are put in series. Therefore, low propagation and coupling loss are critical to retain light signal integrity as the light transmits through the network. Finally, from a product development aspect, various silica based fibers with special properties, such as amplifying, exist from the well-established optical fiber industry. The availability of these specialty fibers in the market place speeds up the fiber based device development dramatically.

However, several drawbacks and limitations exist when using fibers to manufacture component devices and integrate a number of devices and channels into a small volume. One of the major drawbacks concerns the lack of automated technologies to handle fibers in device fabrication process. The requirement for high optical precision in fiber alignment becomes more challenging when multiple number of fibers are integrated. Another issue is the limitation of minimal bending curvature. A silica based single mode fiber cannot have bending radius smaller than a few centimeters, beyond which light signal may be lost or permanent fiber damage may occur. This has significantly limited the progress of reducing the size of fiber based devices when more components are desired to be compacted into a system. Even though simple devices such as splitters and couplers can be readily produced by fiber fusing, difficulties exist to fabricate major DWDM components such as MUX/DMUX from fibers. Multi-layer thin film filter based DWDM devices have been used to combine or separate light signals with different wavelengths. The combination of both fiber based devices and thin film filters require free space optical devices such as lens and light collimators. All of these complexities increase the cost of device fabrication and packaging. As more channels are demanded by system manufactures, it is clear that existing component platforms based on fibers and filters will not provide an economical path into future multi-channel integrated devices. As system manufacturers aim to further reduce costs, it is highly desired to build devices with high channel count and a greatly reduced foot print. This demand has motivated component manufacturers to produce integrated solutions by taking a planar integrated approach.

Planar lightwave circuits have been extensively studied and developed at both research and commercial level[2][3]. Waveguides, amplifiers, lasers, gratings and filters made on a planar substrates have been produced in various research labs. Among them, Arrayed Waveguide Gratings (AWG)[4] are one of the few chip type devices that have been commercialized. Several base materials including silica, InP and $LiNbO_3$ have been used to fabricate PLCs. Ion exchange techniques have been used to produce core regions with higher indices than clad in waveguide fabrication from InP and $LiNbO_3$ single crystal substrates. Lithography and etching techniques have been used to fabricate waveguides based silica-on-silicon technology. More efforts have centered on silica-on-silicon technology due to its ease in coupling to silica-based fibers with minimal coupling loss. In the simplest form of this structure, the doped silica core layer has a slightly higher index value than that of under clad and top clad. A single mode light wave may be confined into the core region by a physical guide structure generated by semiconductor lithography and etching. The dimensions of the waveguide cross section is typically 7 x 7 microns; close to the dimension of the core of a silica single mode fiber. The match of this physical dimensions and silica refractive index in both fibers and planar chips is critical to maintain mode properties as well as to minimize coupling losses. From a manufacture prospective, the ability to utilize existing well developed semiconductor fabrication processes is critical to fabricating multiple numbers of planar chips on a single wafer substrate to achieve the low cost values based on per device or per channel. As the feature size for silica-based waveguide structures are on the order of microns, it is considered well in the range of existing standard semiconductor processing capability.

In general, optical integrated circuits (OIC) resemble electronic integrated circuits (EIC) in that both integrations concern: (1) packing more functional devices onto a small footprint; and (2) producing multiple number of integrated device on one silicon wafer substrate. However, many key differences exist in the fabrication details due to differences in the physics governing the electrons and photons. For example, silica has been used in EIC as diffusion barriers, insulators and dielectrics to achieve various electronic functionalities. However, silica in OIC has completely different functions as light confining and transmitting media. This major difference leads to a demand on entirely different sets of process requirements to achieve high quality silica films. The technologies designed and developed for EIC in general cannot be borrowed to apply in OIC fabrication without modification. Even though several forms of semiconductor CVD processes can produce thin film silica, they have difficulties in producing silica films with higher than micron thickness while maintaining high optical quality and reasonable deposition rate. The stress induced in the films at high deposition rates are also an issue that can lead to cracks in the final glass film. Therefore, technologies fundamentally designed for planar glass deposition are highly desired in the rapid development PLC based devices.

Fabrication of PLC devices based on silica-on-silicon technology is comprised of many steps including optical circuit design, under clad deposition on a substrate, core layer deposition, lithography and reactive ion etching (RIE), top clad deposition, fiber to chip alignment and attachment and final device packaging. Two current deposition technologies are Chemical Vapor deposition (CVD) and Flame Hydrolysis Deposition (FHD)[5]. Both have played major roles in depositing glass films as under clad, core and top clad. Both have shown commercial level success in the development of OIC devices based on silica-on-silicon technology. In both of these two approaches, high purity chemicals such as $SiCl_4$, $GeCl_4$, and $POCl_3$ have been used as precursor reactants. These precursor chemicals react on a heated substrate to form dense glass films (CVD) or to react in a fuel and oxygen mixture flame to form glass soot particles and immediately deposit them onto a substrate (FHD). In both cases, a second step of thermal treatment is required to produce glasses with high quality optical properties and low propagation loss. CVD produced films in general need an annealing process around 600 - 800 C without major molecular level reorganization, whereas the films produced by FHD need a consolidation process around 1000 - 1300 C with major molecular level reorganization through melting.

FHD processing was developed and commercialized to produce glass films on planar substrates. The waveguides produced from a FHD core layer have been found to have a propagation loss as low as 0.05 db/cm. Various optical films with functionalities including amplification, UV sensitivity and high optical transparency have been researched in the past. Active devices including lasers and amplifiers have been produced and reported by various research groups. One of the major advantages of the FHD process is that a thick layer of porous glass film form after the glass soot deposition. Before subsequent consolidation, this porous glass soot layer can be loaded with other dopants such as rare earth element by using a solution doping technique developed in fiber optic industry. Another advantage of the FHD technique is that it has very low stress formation during the glass soot deposition step. This is because the interaction between the soot particles is much weaker compared with atomic bonding action occurred in the case of CVD deposited film. High volume of glass soot materials can be coated on the surface of a planar substrate. Such volumes of glass soot materials will be subsequently converted into thick glass film by a thermal consolidation. Unfortunately, FHD is limited by the lack of flexibility of tuning flame temperature. It is mainly determined by the mix ratio of hydrogen containing fuel and oxygen. The flame temperature is one the most important parameter that affects the properties of glass soot particles and their subsequent sintered glass. Another issue with FHD equipment design is that the flame jet nozzle is vulnerable to deterioration when exposed to a high temperature corrosive environment. Any alternation of the nozzle opening would lead to a change in the glass soot characteristics deposited on the substrate. Furthermore, the nozzle dimensions in FHD are much smaller than the dimension of the substrate on which the soot particles will land. Thus it takes many passes to cover the materials onto the entire substrate surface. This adds process complexity and generates non-uniform features caused by the trace of relative scanning motion between the flame jet and the substrate. In addition, it will also require longer process time to carry out coatings, leading to low throughput of coated wafers. Finally, as the flame is only sustained by the chemical feed, any fluctuation in the delivery of reactants and gases will lead to flame instability. This instability can cause non-uniform coating of the glass soot particles and thereby affect the final glass quality after consolidation.

CVD systems developed both in semiconductor industry and optical fiber industry have been used by many groups to develop thick optical glass films for PLC devices. Low pressure CVD (LPCVD), plasma enhanced CVD (PECVD), and

atomspherical pressure CVD (APCVD) have been used in making planar glass films. Compared with FHD system, CVD is made available as a turnkey operation system. However, one of the major challenges in CVD glass deposition is its low deposition rate. Currently, the average deposition rate used in these CVD processes is around 0.1 – 0.2 micron per minute. Faster rates are possible, but they induce high stresses in the deposited thick glass films that are not easily removed during annealing. This leads to an unacceptable glass media for device applications. At communication wavelength from 1.3 – 1.5 microns, the core layer thickness of a waveguide made of silica glass materials are on the order of 6 – 8 microns as required by physics, based on materials parameters such as the index of refraction of core and clad. They must be highly transparent and have a low light signal propagation loss. This is in sharp contrast with the film thickness and application purposes of silica film used in semiconductor integrated devices. For example, silica has been mainly used in semiconductor applications as diffusion barrier, dielectric layer, and insulators. The silica films deposited by commonly used CVD technology have been found to have acceptable electronic properties and mechanical integrity. However, when silica films are used to transmit and guide light, a much stronger requirement is put on their optical properties such as transparency, film smoothness, degree of birefringence and refractive index uniformity. Due to these major differences between the desired functional properties of fiber optics and semiconductor electronic materials, as well as a contrasts in film thickness, semiconductor deposition technologies must be modified, tailored, or even redesigned to produce these thick films for planar device industry. New deposition techniques fundamentally designed to produce the films with the required optical properties are needed in PLC development.

A novel deposition technology – Laser Reactive Deposition (LRD™) processing combines the advantages of both CVD and FHD processes. We will focus our discussion on the comparison between LRD™ processing and other processes such as CVD and FHD. In particular, we will discuss the high throughput aspect of this technology which radically increases the rates of deposition and improves the efficiency of the planar film deposition process.

COMPARISON OF CHEMICAL VAPOR DEPOSITION (CVD) AND FLAME HYDROLYSIS DEPOSITION (FHD)

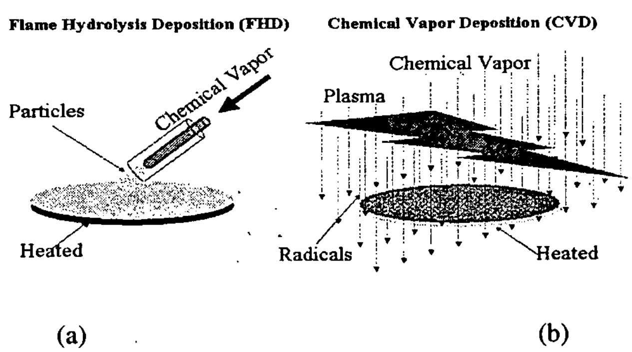

Fig. 1 Schematic charts of CVD (a) and FHD (b) process in glass film deposition.

Shown in Fig. 1 is a schematic diagram of a flame hydrolysis deposition process (Fig. 1a) and a chemical vapor deposition process (Fig. 1b). Details stress the fundamentals in these two technologies and their abilities to deposit planar glass coatings. First of all, FHD processing is comprised of depositing glass soot particles formed in a high temperature flame jet onto a planar substrate such as a wafer. The flame jet is produced and sustained by reacting high purity precursor chemicals such as $SiCl_4$ with a hydrogen containing fuel and oxygen mixture. Other reactants including B, P and Ge may also be introduced into the flame jet along with a carrier gas such as nitrogen or argon. The carrier gas also assists the glass soot particles formed in the flame to have a transfer momentum directed to the wafer surface. By a

computer controlled horizontal progressing motion of substrates, the entire wafer may be coated by glass soot particles. A porous layer of glass soot particles may form on the wafer surface up to several millimeters in thickness. The wafer, loaded with the glass soot particle layer is moved into a oven set at a high temperature around 1000 – 1300 C (The appropriate temperature set point is strongly depending on the concentration of dopants such as B and P). In this consolidation step, the glass soot particles are first melted into a viscous liquid as the temperature is ramped up to the set point. Then the melt is slowly quenched into a final transparent glass coating as the oven is lowered to room temperature. The final film thickness is determined mainly by the amount of materials deposited on the wafer. The deposition rate is thus related with the rate of silica soot particles formation in the flame jet and the capture rate of the soot particles by the substrate.

On the other hand, CVD processing has a rather different mechanism to produce glass coatings. In this case, the vapor of $SiCl_4$ is introduced into the chamber where a silicon wafer is positioned on a heated substrate support. The temperature of the wafer is maintained by an electrical heater or infrared radiation. Reactant vapors are transferred to the wafer surface and react near the heated wafer surface. Film growth occurs as layers of molecular species form when they contact the hot wafer surface. This is in sharp contrast with the FHD process where solid glass soot particles, instead of molecular species are the deposition units. Therefore, the film stress generated during the CVD deposition and FHD deposition is rather different due to fundamentally different interaction forces in each cases. Despite the fact that dense glasses readily form from CVD processing, the as-deposited films are normally not good enough to be used for planar optical device application. A subsequent annealing process must be carried out to remove the stresses in the film and settle the film into a phase that has high optical qualities. Also different from FHD process, the glass film produced by CVD does not go through a molecular level reorganization in the annealing stage. The deposition rate in this case depends on mainly several factors including: (1) the rate of chemical vapor transported to the wafer surface; and (2) the reaction rate on the wafer surface, which is highly depending on the temperature; and (3) the reactivity of molecular species before they react on the substrate surface. To increase the rate of deposition in the CVD process, all these three factors must be controlled to achieve an optimized process.

LASER REACTIVE DEPOSITION (LRD™)

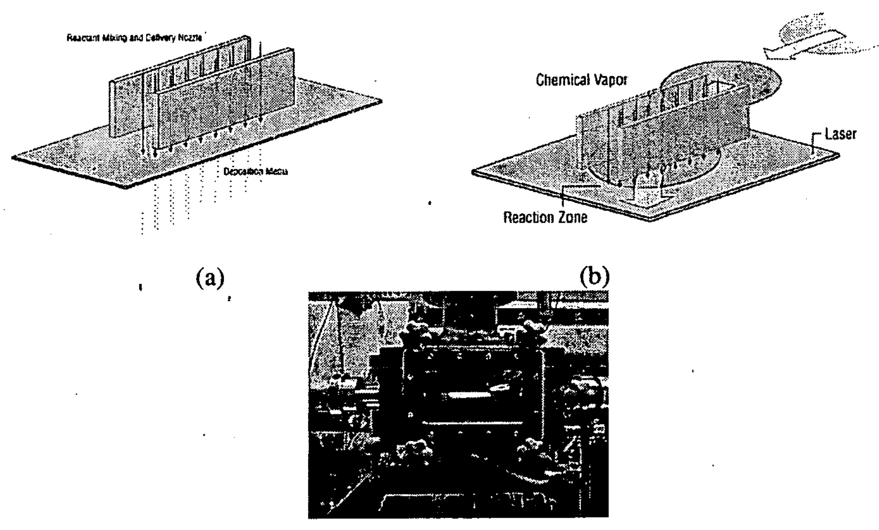

Fig. 2 (a) Nanoscale particle synthesis via NPM™ technology, (b) Nanoscale particle coating via LRD™ technology and (c) LRD™ in operation.

Shown in Fig. 2a and 2b are conceptual charts of our two technologies Nano Particle Manufacture (NPM™)[6] and Laser Reactive Deposition (LRD™), respectively. NPM™ technology has been described in a separate paper about its ability

to produce a range of simple and complex nanoscale materials. In this paper, we focus on LRD™ technology and describe its ability in the glass film deposition. In a drastically different design, we have fabricated a nozzle assembly to deliver precursor chemicals in a sheet flow stream as indicated by the two vertical slabs in Fig. 2b. The vapors of precursor chemicals are introduced into the nozzle assembly and are ejected into a laser beam. The laser beam has an engineered optical assembly giving it a sheet-like profile with its normal direction in parallel with the reactant sheet stream. The laser beam has been indicated by a flat sheet under the vertical slab nozzle. The laser beam is used to drive the reactions between precursor reactants and gas species and produce nanoscale particles. The detailed mechanism is described in a separate paper. The width of the laser beam is larger than that of the nozzle, insuring 100% interception of reactant stream by the laser beam and full reaction of precursor chemicals and to transform into particles. As shown from Fig. 2b, the wafer is transported past the laser beam sheet and gets coated with nanoscale particles formed in the reaction zone, defined by the overlapping region between laser beam and reactant stream. Fig. 2c shows one such reactor in operation.

There are several major differences and similarities of LRD™ with existing FHD processing. First of all, the dimension of the nozzle that deliver the particles is larger than the dimension of the wafer. This has presented a clear benefit in the coating of large area substrate such as wafers from 75 – 300 mm. In addition, the substrate translating mechanism is much simpler for each layer deposition. One layer of glass soot particles on entire wafer can be accomplished in a single pass operation, whereas the FHD needs many passes to cover the wafer with one layer. Secondly, instead of solely depending on the reaction heat from fuel/oxygen mixture in the case of FHD, LRD™ processing employs a computer controllable continuous wave (CW) CO_2 laser beam to initiate and sustain the reactions in the reaction zone. This has added an additional avenue to control the reaction temperature and reaction chemistry inside the reaction zone. In other words, the laser beam produces a controllable, programmable and highly stable heat source to drive the reaction. This significantly improves glass soot coating uniformity. Similar to the FHD process, glass soot particles are formed before they are deposited onto the wafer surface. A subsequent melting and consolidation is required to produce the final optical glass coating. These differences and similarities will be discussed next by a detailed comparison of the three technologies.

LRD™ PROCESS CHARACTERISTICS AND ITS COMPARISON WITH CVD AND FHD

In Table I, we have described the steps used in the glass coating process via three technologies including CVD, FHD, LRD™ processing. In the following, we will discuss several key aspects of the three technologies in their abilities to deposit glass films at high throughput rates. The three technologies have a few similarities in their approach to deposit optical glass films. First of all, all of those technologies use high purity precursor chemicals such as $SiCl_4$, BCl_3 and $POCl_3$. These chemicals have been used successfully in the fiber optic industry to produce high quality fibers. It has been demonstrated in the market place that films produced by CVD and FHD using these precursor chemicals have extremely low optical propagation loss. The same is true in films produced by LRD™ technology since it uses the same set of chemicals as feed stock. In this paper, we will focus on the silica glass coating using chemicals such as those used in common BPSG manufacturing. Secondly, all three technologies require a post deposition process to either anneal or consolidate the as-deposited films into final form of optical quality glass coatings. Either annealing or consolidation processing are batch processes that allow multiple coated wafers to be processed simultaneously. Therefore, the bottle neck of the high throughput production of glass coated wafers lies at the initial glass film deposition.

	CVD	FHD	LRD™
Precursor Chemistry	High purity neat liquid chemicals with high vapor pressure are used as feed stock.	High purity neat liquid chemicals with high vapor pressure are used as feed stock.	High purity neat liquid chemicals with high vapor pressure are used as feed stock.
Reaction Zone	Reaction zone is defined as the near-surface region of a heated substrate.	Reaction zone is defined by the contour of the flame jet formed and sustained by an exothermic reaction of oxygen, fuel and reactant mixture.	Reaction zone is defined by the intersection region of a sheet-like laser beam and a sheet-like precursor reactant stream.
Materials Formation	Glass materials form on the substrate surface through a thermal reaction of reactants driven by the heat from a heated substrate.	Glass materials form in the flame jet reaction zone driven by a exocermic reaction of a mixture of oxygen, fuel and precursor chemical.	Glass materials form in the reaction zone driven by a combination of laser energy and exocermic heat generated from the reaction of oxygen, fuel and precursor chemicals.
Glass Deposition	Glass film grows when more precursor chemical species react on top of previously formed glass films. The films grow across the entire substrate surface at the same time.	Glass films grow by mounting more soot particles formed in the flame jet by a multi-pass process required to cover entire substrate surface with materials.	Glass films grow by mounting more soot particles by a multi-pass process, but each pass covers the entire substrate surface with materials.
Glass Consolidation and annealing	As-deposited dense film is subjected to an annealing process around 800 C. The annealing process is required to produce final glass film in a high quality optical glass.	As-deposited silica soot particle film is subjected to consolidation processing around 1000 - 1300 C depending on dopant concentrations. The consolidation is required to melt and quench the glass soot particles into final dense and high quality optical glass.	As-deposited silica soot particle film is subjected to an consolidation processing around 1000 - 1300C depending on dopant concentrations. The consolidation is required to melt and quench the glass soot particles into final dense and high quality optical glass.

Table I: A step-by-step planar glass fabrication process comparison between three glass deposition technologies including CVD, FHD and LRD™.

Despite of the similarities in the three technologies, clear distinctions between LRD™ processing and CVD and FHD technologies exist in several aspects. They are summarized in the following: (1) LRD™ processing has a sheet jet nanoparticle stream to cover an entire substrate in one sweep; (2) LRD™ processing uses computer-controlled laser beam power to drive the critical reaction; and (3) LRD™ processing uses an extended nozzle assembly capable of delivering glass soot particles at high rate (~ 1 kg/hour). These three characteristics are unique in the LRD™ technology. Moreover, LRD™ processing shows a clear design merit to achieving high throughput glass coatings. First, the nozzle assembly allows high volume of precursor chemicals and gases to be delivered into the well-defined reaction zone. Secondly, a powerful laser beam is able to drive virtually 100% reaction yield to transform the reactants into solid nanoscale particles. Thirdly, the laser beam produce a flat sheet of particle stream that have a width larger than the dimension of the wafers. Finally, the nanoscale glass particles produced at the rate up to 1 kg/hour can be captured by the substrate. These key process advantages essentially removed all the bottle necks in the glass film deposition experienced by both FHD and CVD. A much shortened glass soot deposition process may be achieved by leveraging these advantages through LRD™ technology. Finally, we stress that the use of laser beam to drive the reaction is a critical aspect to achieve an uniform sheet of particle stream. A simple fuel and oxygen mixture flame has great difficulties to produce an uniform reaction zone and maintain the stability of the flame across the entire nozzle length. In addition, the laser beam plays a major role in the reaction chemistry of these reactants inside the reaction zone as described in a separate publication. Shown in Fig. 3a is as deposited glass soot film produced by LRD™ processing with a thickness of a few millimeters. Fig. 3b shows a SEM image of a consolidated glass film from a LRD™-produced glass soot coating. The thickness of this consolidated film is around 5 microns. A deposition rate around 10 microns per minute is used routinely. It is clear from the SEM picture that a smooth surface of the silica coating is achieved. The

signatures at the interface between Si substrate and silica are due to the minute cracking induced at sample preparation for SEM imaging.

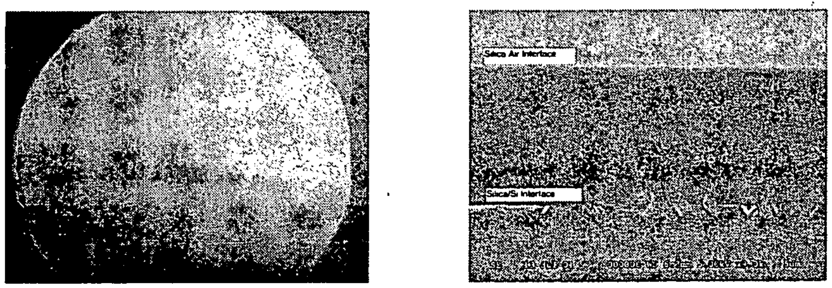

Fig. 3 Optical image of an as-deposited glass soot film by LRD™ process (a) and a Scanning Electron Microscope image of a 5 micron thick consolidated glass film.

SUMMARY

In this work, we have demonstrated a planar glass deposition rate of approximately 10 microns per minute using our LRD™ technology. We have compared in details the process of three major commercial technologies including CVD, FHD, and LRD™ processing at fundamental levels. The key attributes of LRD™ technology are: first, a sheet jet nanoparticle stream to cover an entire substrate in one sweep; Secondly, the use of a computer controlled laser beam to drive the reaction that forms glass soot particles. Thirdly, the use of an extended nozzle assembly capable of delivering glass soot particles at an extremely high rate up to 1 kg/hour. These three characteristics are unique in the LRD™ technology. In conclusion, we have developed a technology that is designed fundamentally for planar glass deposition. This is considered to be highly desired in the development of integrated PLCs to achieve low cost manufacture of optical devices.

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